TOPOGRAPHIC EFFECTS ON FLOWING LAVA: ANALYSIS OF SMALL AND INTERMEDIATE SCALE PERTURBATIONS; Patricia G. Rogers, *NASA Headquarters*; Maria T. Zuber, *Massachusetts Institute of Technology*

The physical properties of lava flows have been studied through field observations as well as through analytical and numerical modeling. Theoretical models of lava flow emplacement attempt to understand how the complex interaction between a flow's physical properties and emplacement characteristics lead to the final flow dimensions and morphology observed in the field. A flow's effusion rate, rheologic parameters, and the underlying topography all play an important role in determining morphologic parameters such as length or surface structure. Therefore, understanding how a flow dynamically interacts with its environment and develops characteristic dimensions and surface features can provide important constraints on its emplacement history.

This analysis is a theoretical examination of the role of pre-existing topography on lava flow emplacement. Specifically, the effects of small- and intermediate-scale underlying topography on the dynamics of the flow are examined. A small-perturbation analysis is used to determine an approximate analytical solution for flow of lava down a rough inclined plane in which the amplitude of the plate undulations are small relative to the depth of the flow. We start with the simple case of a single harmonic component on an inclined plane. This analysis is expanded to examine viscous flow down a more natural surface, represented by topographic profiles of Hawaiian basalts. We next examine the cumulative influence of pre-existing topography at intermediate scales. Specifically, we determine how a flow down an inclined plane reacts to periodic or random slope changes, and the effects on the resulting planform of the flow.

Small-Scale Topographic Effects. We examine a first-order solution of a lava flow, modeled as a viscous liquid, flowing down an underlying rough surface represented as a two-dimensional corrugated shape with the corrugations running parallel to the y-axis (crossflow) [1]. We solve the Navier-Stokes equations for a viscous, incompressible fluid subject to a gravity force and focus on flow in two dimensions (x and z). We start with a plane with a superimposed wave of a known amplitude and frequency, then extrapolate this approach to an even more realistic surface by combining multiple harmonic components. As a first order approximation, we consider the flow near the vent which is at such high temperatures that a Newtonian approximation is valid, that is shear stress is linearly proportional to the rate of deformation.

The first-order approximation for the upper flow surface due to one underlying harmonic component is expressed as:

$$g_1 = Ce^{i\lambda x} \tag{1}$$

which is a complex number with both an amplitude and a phase component, where C is a function of the topographic wavelength and the slope of the ground.

Multiple Harmonic Solution. Next we wish to address a flow's sensitivity to changes in the underlying surface roughness at a range of scales. Of primary interest is the critical scale at which the flow is deep enough, relative to the topography, such that details in this topography are not significant to the overall flow emplacement. Superposing multiple harmonics on the mean slope can be used to represent a more natural surface, composed of topographic irregularities of varying wavelengths. We use as our baseline topographic profiles collected on several Kilauea basalt flows [2] which span a wide range of surface roughness, from smooth pahoehoe flows to jagged a'a deposits. For the smoothest and roughest surfaces measured, we calculated the Fourier transform of the profile and applied the above model for a range of flow depths.

Results. From this analysis we find that if a flow is very thin, the ground slope is large, or the wavelength of the plate roughness is very long, the upper surface of the flow closely mimics the lower surface shape. As the flow thickens, the plate wavelength decreases, or the average topographic slope decreases, the amplitude of the upper surface undulations decrease. The lava flow acts as a low-pass filter for the underlying surface roughness, such that high-frequency changes in the ground are smoothed in the final flow shape. Tradeoffs between the mean ground slope and surface roughness are explored to determine at what scale (relative to the flow depth) these effects begin to significantly influence flow emplacement. We find that the flow on steeper slopes appears to mimic the underlying topography better than flow over shallower slopes. We also find that the phase shift is small for short-wavelength perturbations. As the slope increases, the maximum phase shift at any given wavelength decreases. The phase shift is greatest for long wavelengths and small slopes, however, the amplitude of the surface displacement at this range would be extremely small and thus would not likely be readily discernible.

Intermediate Scale Topographic Effects. We next examine the influence of pre-existing topography on internal flow dynamics at an intermediate scale. One approach is to determine the cumulative effects of slope changes and different types of systematic and random topographic variations downflow on the flow width and depth. Again we assume a steady, incompressible, low Reynolds number, Newtonian flow. We model the downflow changes in depth and width for an unconfined flow on an inclined plane, assuming conservation of volume after [3]. A volumetric flow rate expression, common to many forms of geologic mass movements, is used [4]:

$$q = \alpha(x)h^m \tag{2}$$

where α is a function of the slope, horizontal dimension (x), and rheologic properties; h is the flow depth, and m is an empirical constant which describes the rheology of the fluid. For a Newtonian fluid with a constant viscosity, m = 3 and $\alpha(x) = \alpha_o = g\sin\theta/3\nu$.

If the x-axis is downstream, and the y-axis is crossflow we have:

$$\vec{q}_{crossflow} = -g\,\alpha(x)\,h^m\cos\theta\frac{\partial h}{\partial y}, \qquad \text{(pressure driven)} \tag{3}$$

$$\vec{q}_{downflow} = -g\,\alpha(x)\,h^m\left(\cos\theta\frac{\partial h}{\partial y} + \sin\theta\right), \qquad \text{(pressure and gravity driven)} \tag{4}$$

The general solutions for h (x,y) and w (x) have several interesting properties which differ from solutions for steady-state lava flow shape. The primary feature is that the width of the flow (in the y-axis) is related to the integrated effects of slope along the entire travel path between the source and a point x. This makes physical sense in that a lava flow does not instantaneously react to slope changes; widening or narrowing occurs at a finite flow rate. We use this model to examine the effects of downflow slope changes on the width and depth of the lava flow, and the resultant margin shape which is produced. In practice, this is accomplished by deriving a moving average of the local cot θ terms along the entire path up to a given x-location.

Results. In order to separate the downflow effect due to changes in a fluid's rheologic properties (such as viscosity) from effects due to pre-existing topography, we start by keeping the slope α constant and examining tradeoffs between flow depth and width over various forms of topography. In each case we examined a baseline solution of a flow over a smooth inclined plane, then considered the effects of adding topographic roughness. This roughness is represented by a synthetic surface of fractal dimension 1.5 (Brownian noise) [2], and we increase the rms slope (the standard deviation of slopes measured between adjacent profile points) to examine roughness of progressively higher amplitude. At these scales we see that increasing the tilt of the mean surface has some effect on the downflow width, but flow over topography with random changes in local slope has no significant effect on the flow shape, even for steep slopes. However, systematic or periodic topography does have a significant effect on downflow width causing the flow to widen significantly with distance from the vent, relative to the smooth plane case, and marginal step increases to occur.

References: [1] Wang, C.Y., *A. I. Chem. Eng.*, 27, 207-212, 1981. [2] Campbell, B.A. and M.K. Shepard, *J. Geophys. Res., 101*, 18,941-18951, 1996. [3] Bruno, B.C., S.M. Baloga, and G.J. Taylor, *J. Geophys. Res., 101*, 11,565-11,577, 1996. [4] Weir, G.J., *N.Z.J. Sci.*, 25, 197-203, 1982.